To: Steering Committee, Project prepared for HORIZON-INFRA-2025-01-SERV-03

Letter of intent for Working Package **Hadron Enigmas: Quantum Virtual Access**

Resulting from the fusion of earlier letters of intent QuantHad and Hequba

Acronym: **HEQUVA**

Project leader: **Yassid Ayyad**

1. Research objectives (classified as per the template from the steering committee).

- **Short-term R&D, Theory and phenomenology**

We intend to find, improve, and classify algorithms that prepare the Hadron Physics community for any advances in Quantum Computing, which help address the following enigmas in hadron physics that cannot, at present, be treated from first principles in full:

a) Computation of observables related to time-evolved operators such as Fragmentation Functions, Transverse Momentum Distributions, etc. Quantum computing is a natural tool here as one can encode the Hamiltonian and advance in real-time (canonical or light front) steps.
b) Properties of hadron matter at finite density (in particular, the Equation of State in neutron stars, but perhaps also transport coefficients) because the statistical physics formulation with a chemical potential has no sign problem on a quantum computer, unlike in lattice gauge theory.
c) More generally, systems out of equilibrium, such as those found in heavy-ion collisions or Nuclear Matter, where again the ability to discretize and step in real time allows one to naturally access correlators at different times.

d) Nuclear properties that can be investigated through the analysis of correlations among nucleons, including phenomena such as pairing, clustering, and collective motion. These correlations provide critical information on structural characteristics—such as shell closures, nuclear deformation, and excitation modes—thereby enabling a deeper understanding of the fundamental interactions and symmetries that govern nuclear structure and dynamics.

We will appraise the computational cost of these algorithms by running demonstration pieces in the existing and upcoming quantum computers, particularly the new 50 qubit machine at the upcoming laboratory jointly operated by the Instituto Galego de Física de Altas Enerxías (IGFAE) and the Galicia Supercomputing Center (CESGA) in Santiago de Compostela, to which virtual access would be granted, as well as the existing one at DESY-Zeuthen and others which may appear.

- **Computing, AI technologies**

The project would center on facilitating the preparation of algorithms and programs of interest for our field for quantum computing platforms, for researchers in our group and across hadron physics. A new laboratory dedicated to analogue quantum simulation will be established and equipped, centering around research in particle and nuclear physics. This facility will be based on a trapped-ion simulator and quantum computer from Alpine Quantum Technologies (AQT), a spin-off company of the University of Innsbruck and the Institute of Quantum Optics and Quantum Information at the Austrian Academy of Sciences. The laboratory's capabilities will be enhanced in January 2026, when an AQT Pine Set-Up is scheduled for installation at the IGFAE-CESGA site. In addition to these developments, CESGA also hosts QMIO, a digital quantum computer, extending the range of quantum computing platforms accessible for research and innovation. Additionally, an autonomous R&D initiative focusing on trapping devices will commence with the commissioning of an extra ion trap setup, facilitating service scalability and fostering a robust research and development program within the laboratory.

- **Applications and links with industry**

The Univ. of Santiago de Compostela will install and make available a commercial trapped-ion analog (as well as digital) quantum simulator provided by Alpine Quantum Technologies. Analogue quantum simulators hold significant promise for hadron physics by enabling the efficient modeling and exploration of complex quantum many-body phenomena that are challenging for classical computation. These platforms can simulate intricate interactions and correlations within hadrons and nuclear matter, aiding in the discovery of new states and phases relevant to strong-force dynamics.

Beyond fundamental research, the ability to emulate quantum processes at this level also supports advancements in related industrial sectors, such as materials science, drug development, and energy, by providing deeper insights into quantum interactions that underpin hadronic structure and reactions. Thus, analogue quantum simulation bridges fundamental hadron physics with practical applications, driving innovation across science and industry. The IGFAE-CESGA laboratory is optimally positioned to address key priorities outlined in the Horizon Europe Work Programme 2026-27 (Digital, Industry, and Space, Quantum Computing – Call for the 2nd SGA for the FPA on trapped-ions), with a primary focus on hadron and nuclear physics. By leveraging state-of-the-art quantum technologies, the laboratory will drive collaborative research, support technological innovation, and enable the development of digital solutions and quantum applications.

- **Training (users' training and support activities)**

The two networked meetings will focus on training hadron physicists who may be considering joining quantum computing activities, also outside the institutions proposed here. They will be implemented as sections of (or collocated) with other major conferences in the field, both to avoid multiplication of events as well as to maximize exposure outside the already informed community, to increase the impact of the initiative.

2. Transnational Access infrastructures (TAs), Virtual Access projects (VAs)

The main focus of the virtual access is to provide access to the new machine at Santiago, but the subproject also includes the collaboration of CERN, through the Theory department and the Quantum Initiative, and the ECT*, both TAs and centers of interest for smaller institutions with research lines in theoretical physics and phenomenology, as well as DESY-Zeuthen with an additional working quantum computer focused on aspects of Quantum Computing for Hadron Physics and Chromodynamics.

An important focus is the facilitation of Virtual Access to Cloud Computing Services providing Quantum Computing capability, with the following actions in mind:

- To assist experienced hadron scientists who have not worked on Quantum Computing before to effectively learn to use the available platforms and prepare their first demonstration codes so their groups become adept at minimum Quantum Computing.
- To provide scientists at smaller institutions with the expertise and the capability to develop algorithms and access those platforms so as to bring talent to the field wherever it may be found in the EU and countries associated with its research programs.
- The capabilities of this laboratory will be boosted by introducing a unique collaboration scheme: researchers may request assistance to map complex nuclear Hamiltonians onto ion-trap analogue simulators, leveraging the expertise of IGFAE-CESGA scientists in quantum control and simulation techniques to model nuclear interactions, explore many-body phenomena, and validate theoretical predictions through precise, experimentally accessible quantum simulations.

3. Estimated budget request

125k euro in **personnel** costs (as copayment to the Univ. of Santiago hosting the postdoctoral researcher of the working package, who will take the role of research enabler for other participants and interested parties). Any remaining funds will go towards providing access to the new quantum computer there.
15k euro to assist with the secondment of the postdoctoral associate to two other centers of the network at DESY-Zeuthen and ECT*, for periods of three months each at least.
50k euro in **travel and networking** costs (as copayments to organize the two activity workshops and also to facilitate the travel of group members to the overall grant-reporting meetings of the project).

10k in **external** provision of cloud **computing** services (to purchase demonstration time from alternative quantum computing providers for the various institutions participating in the subproject)

200k euro total (3% of the overall grant)

4. Participating and partner institutions

Initial members (in alphabetical order of institution's legal name). We are open to further additions.

Institution	Geographical location	Contact members	Additional collaborators
Conseil Européen pour la Recherche Nucléaire CERN	Geneva, Switzerland	Sofia Vallecorsa	Enrique Rico Ortega, Joachim Kopp
Deutsches Elektron Synchrotron	Zeuthen, Germany	Stefan Kühn	Karl Jansen
European Center for Theoretical Nuclear Physics and Related Areas ECT* and U. Trento	Trento, Italy	Alessandro Roggero	Daniele Binosi
Instituto Superior Técnico (of the University of Lisbon)	Lisbon, Portugal	Joao Seixas	Yasser Omar
Laboratoire de physique des deux infinis Irène Joliot-Curie (IJCLab), Paris-Saclay University	Orsay, France	Denis Lacroix	
Universidad Complutense de Madrid	Madrid, Spain	Felipe J. Llanes Estrada	Pia Zurita
Universidad de Granada	Granada, Spain	María Gómez Rocha	Juan Carlos Criado, Lorenzo Luis Salcedo
Univ. Santiago de Compostela - IGFAE (and Centro de Supercomputación de Galicia, CESGA)	Santiago, Spain	Yassid Ayyad (USC-IGFAE)	Carlos Salgado (USC-IGFAE) Lois Orosa (CESGA) Ignacio López Cabido (CESGA) Wenyang Qian (USC-IGFAE)